PULSED POWER APPLICATIONS OF THE PLASMA EROSION OPENING SWITCH

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Abstract

The Plasma Erosion Opening Switch (PEOS) has been shown to be a useful tool in improving the operation of various pulsed power devices. Applications include prepulse suppression, risetime sharpening, pulse compression, and voltage and power multiplication. Successful modeling of the switch operation has been performed using a switch model coupled to a transmission line code under a variety of circumstances. Some examples illustrating switch operation as predicted by the switch model will be presented.

Introduction

The Plasma Erosion Opening Switch (PEOS) has been under investigation for several years for applications to existing and planned pulsed power generators.[1-5] This fast opening switch has been shown to conduct megamperes of current for 10's of nanoseconds and to open in 10 nanoseconds or less. The switch then remains open against voltages of several megavolts. Many different experiments have been performed using this switch for different applications. The most common use to date has been for pulse shaping and power conditioning on existing pulsed power generators. Depending on the switch design it can eliminate prepulse or divert some fraction of the generator pulse to give a fast risetime.[6,7] The switch can also improve magnetically insulated transmission line power flow, symmetrize pulses from multi-generator systems[5] or lower voltages across vacuum insulators. It has also been used for inductive energy storage and pulse compression and produced greater than factor of two voltage gains into diode loads.[8]

This paper will discuss several aspects of the switch which provide a basis for scaling the switch operation. Some data from experiments performed on the Gamble II generator at high power levels will be presented and a comparison of this data and the results of applying a theoretical model of the switch operation[9] will be discussed. The paper will then demonstrate several aspects of the switch operation using the switch model including density and load impedance effects and scaling of the switch to a higher voltage and power system similar to the PBFA II generator presently under construction at Sandia National Laboratories.[10]

PEOS Operation

The model of the operation of the PEOS has been described in detail elsewhere.[9] The treatment in this paper will be limited to a general discussion with emphasis on aspects of the switch operation to be illustrated by the subsequent computer modeling. There are basically three phases in the operation of the switch. These phases are the closed or conduction phase where the switch remains at a low impedance, the opening or erosion phase where the switch impedance rapidly increases from milliohms to 10's of ohms, and the open phase where the switch remains at high impedance and power from the generator or the inductive store is delivered to the load.

The switch uses a preformed plasma which is in place before the generator pulse. The plasma ions have mass number A, charge state Z, density N_i, and an average drift velocity v_d. Existing plasma sources can produce ion flux current densities of up to 100 A/cm^2. The switch uses this flux of ions injected toward the cathode to provide the ion component of a bipolar Child-Langmuir like current sheath formed near the cathode surface when voltage is applied across the switch. The voltage across the switch is believed to be primarily across the switch gap near the cathode surface during the conduction phase. The effective ion current density supplied by the plasma during the conduction phase is

$$J_i = ZeN_i v_d \quad \text{A/cm}^2. \tag{1}$$

The current density which this flux of ions can support is

$$J_T \approx J_e = \left(\frac{Am_p}{Zm_e}\right)^{1/2} J_i \quad \text{A/cm}^2 \tag{2}$$

where m_p and m_e are the proton and electron masses, e is the electronic charge, and J_T (J_e) is the total (electron) current density. These two equations and the switch area set the limit on the amount of current that can be conducted during the conduction phase of the switch operation.

When the total current driven through the switch exceeds the limit imposed by the plasma source and Eqs. 1 and 2, any further increase in current will start to remove ions from the plasma and to open the gap . This erosion process starts the opening phase. As the gap opens, the impedance of the switch as well as the voltage across the switch gap increases. This voltage is also across the parallel load impedance and eventually becomes large enough to drive current through the load. Erosion by itself is too slow to account for the observed switch operation. Enhancement of the process occurs when the magnetic field bending of the electrons in the gap starts to insulate the electrons from crossing the switch gap. This leads to an excess of electron space charge near the plasma-gap interface and causes an increase in the number of ions extracted from the plasma. The enhancement process can result in more than an order of magnitude faster opening than simple erosion and can explain the observed fast opening of the switch.

The final phase of the switch operation occurs when sufficient current is driven through the load that the switch electrons become completely insulated. The load current I_L must be greater than the critical current I_{crit} in the switch region if the switch is to be completely open.

$$I_L > I_{crit} = \alpha_1 8.5(3)(\gamma^2 - 1)^{1/2}\frac{R}{D} \qquad \text{Amp} \tag{3}$$

where α_1 is a factor of order 1, γ is the relativistic factor, R is the cathode radius in the switch, and D is the gap width. Equation 3 shows the interdependence of the load impedance, which along with the load current determines the voltage and γ, and the switch geometry which enters the equation through the cathode radius and the switch

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14. ABSTRACT

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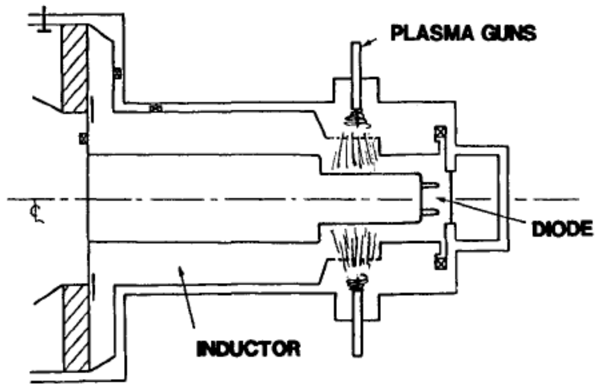

Fig. 1. Schematic of the Gamble II system.

gap. The switch will remain open as long as the current through the load is sufficient to magnetically insulate the electrons emitted off the cathode in the switch region. The better the magnetic insulation, the higher the impedance of the switch.

A large number of experiments have been performed to investigate the physics of the PEOS operation.[8] The model of the switch operation has thus far been consistent with the experiments and has been able to predict switch operation under a variety of circumstances.[9,11]

Gamble Experiments

Experiments using a PEOS have been performed on both the Gamble I and Gamble II generators at NRL.[1,12] The Gamble II system is shown in Figure 1. The plasma is injected into the switch region by carbon plasma sources[13] located downstream of the 100-nH coaxial vacuum inductive store region. The 100-ns FWHM Gamble II generator pulse can drive up to 1.2 MA in the system. An electron beam diode is located downstream of the switch.

Figure 2a shows some measured voltage and current traces from a Gamble II PEOS shot. An 8-ohm pinched-beam diode was used. The load voltage was inferred from x-ray diagnostics and agreed well with inductively corrected voltages. The currents through the switch and the load are shown. The plasma source used for this experiment limited the peak switch current to ~ 400 kA. When the switch opens the current in the load rises in ~ 10 ns transferring nearly all the current into the load. The 3-MV peak voltage is twice the matched load voltage for this system and greater than the open circuit voltage at this charging level. Diagnosis of the load voltage is difficult due to insulator flashover and the lack of reliable and nonperturbing voltage diagnostics for the load end of the machine.

A computer code based on the theory synopsized in this paper and described in detail elsewhere[9] was coupled with a transmission line code[14] to model the switch operation. A realistic fit to the Gamble II open circuit waveform was used in the transmission line circuit which was terminated with an 8-ohm constant impedance load. The switch parameters used in the code runs were based on the experimental values. The plasma density was set at 8.5(12) cm^{-3} of C^{2+} ions with an injected drift velocity of 10 cm/μsec. The switch cathode (anode) radius was 2.5 (5.0) cm and the switch was 15 cm long. The results are shown in Fig. 2b. The peak values of the currents and voltages agree with the experimental results.

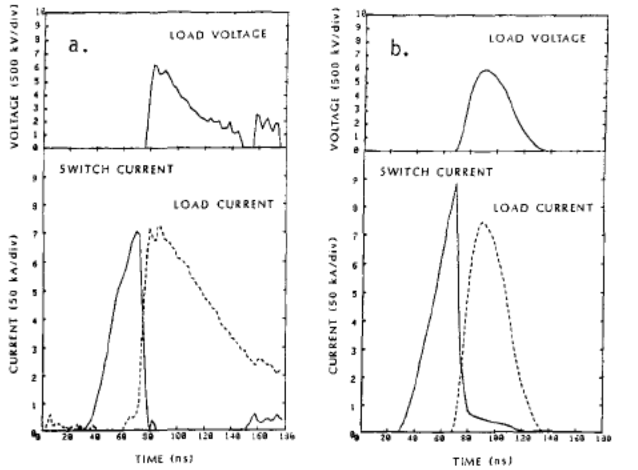

Fig. 2. (a) Gamble II PEOS results, (b) Computer model of Gamble II results.

Similar agreement between experiment and theory for the Gamble I and Gamble II experiments has been obtained over a wide variety of experimental conditions. Scaling of the switch operation in the 150 kA - 1 MA regime has been investigated experimentally on the Gamble machines and the results have been modeled. Good agreement over the entire range of experiments has been obtained.

Generic Switch Simulations

Some aspects of the switch operation can be demonstrated by running the switch code under various conditons. A more generic circuit model and input voltage waveform were used for simplicity and generality. The basic results can be applied to many cases. The circuit used is shown in Fig. 3. A voltage generator with $\sin^2$ voltage waveform, a peak voltage V_{MX} and a given FWHM drives current through the generator impedance R_{GEN} and inductance L. The switch impedance R_S starts very low and increases later on depending on the interaction of the switch and the circuit. A closing switch with a 200 kV closing voltage located between the switch and the load represents the turn-on threshold for the field emission diode load impedance R_L.

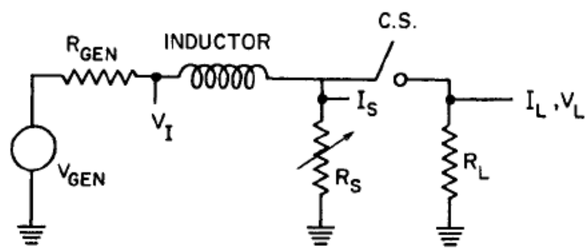

Fig. 3. Simplified circuit model.

The first simulation presented uses parameters similar to the Gamble II system. The generator impedance was set at 2 ohms, the peak open circuit voltage was 4 MV and the FWHM was 100 ns. The 4-MV operation represents a full charge on the Gamble II Marx rather than the 3 MV charge normally used in experiments. The storage inductor was 100 nH as in the Gamble experiments. Two sets of runs were done varying first the injected plasma density and second the load impedance.

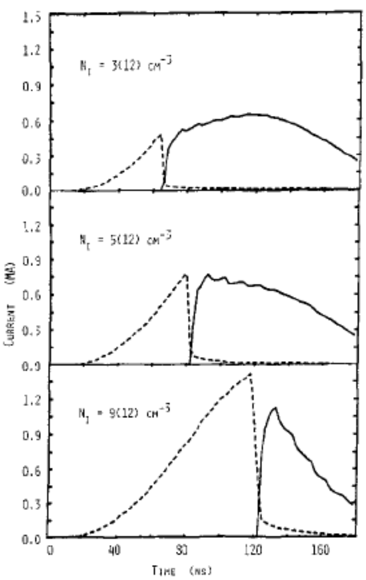

Fig. 4. Gamble II switch density variations.

Figure 4 shows the results of varying the injected plasma density while keeping the other switch parameters fixed. The switch parameters were 2.5 cm cathode radius, 5 cm anode radius, 15 cm/μsec plasma drift velocity and 20 cm axial length. A 4-ohm load impedance was used. The three cases show 3, 5, and 9(12) cm^{-3} switch plasma densities. The 3(12) cm^{-3} case shows the effect of a low plasma density injected into the switch. The switch starts to open after 40 ns of conduction time. The current is 450 kA at the time of opening. The generator is still driving the system with the 4-ohm load impedance after the switch has opened. At this switch density a nearly flat load voltage pulse is obtained. The second case with 5(12)cm^{-3} switch density delays the opening for another 20 ns with a peak switch current of ~ 750 kA. The <10 ns load current risetime gives a roughly saw-toothed output pulse. The generator is still driving the load impedance directly with peak voltage occuring at 100 ns. The final case at 9(12) cm^{-3} shows an inductive store case with the opening occurring after the peak generator voltage. The peak switch current of 1.4 MA drops suddenly when the switch opens. The load current reaches only 1.1 MA because of the resistive decay of the current during the 10 ns opening time. The output voltage pulse is still 4.4 MV which exceeds the driver open circuit voltage and the pulse width is down to <30 ns. In this case most of the energy has been stored in the inductor during the conduction phase and then delivered to the load after the switch has opened. These three examples illustrate the effect on the output pulse of changing the switch density. This result suggests that the switch can be tuned to provide a wide variety of output pulse shapes.

A second example is shown in Figs. 5a and 5b. In these simulations the same switch parameters as in the 9(12) cm^{-3} case were used and the load impedance was varied. Figure 5a shows the load voltage for several different load impedances. The 2-ohm case has a peak of 2.7 MV. As the impedance of the load is increased the load voltage also increases. A peak of nearly 8 MV is reached for a 10-ohm case. The pulse width remains ~30 ns for all the load impedances. Figure 5b shows the switch gap for these same cases. According to Eq. 3 if the

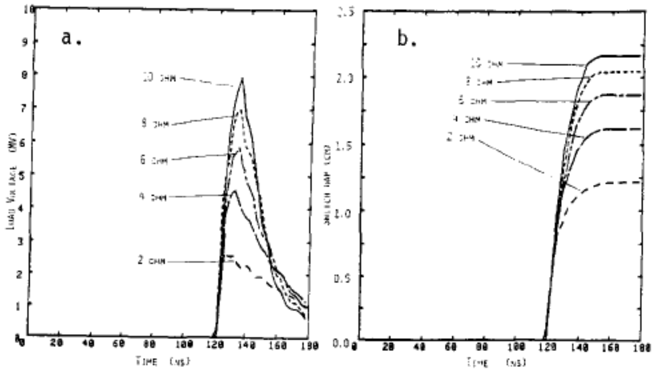

Fig. 5. (a) Load voltage versus load impedance, (b) Switch gap versus load impedance.

voltage increases at a constant current (i.e. when the switch opens at the same time for a given system) then the gap must also increase if the electrons emitted in the switch region are to be magnetically insulated from the switch plasma. As the voltage increases the gap increases in a self-consistent manner in order to maintain the magnetic insulation. Losses in the switch appear when the switch does not open to a large enough gap to allow complete magnetic insulation. Larger load impedance runs show current loss in the switch region and thus lower voltage. The larger gaps with the increased voltage (load impedance) illustrate the interaction of the switch and the load.

High Voltage System Simulation

For another example of the switch operaton, a high voltage, high impedance system is presented. This case is similar to one half of the PBFA II system presently under construction at Sandia National Laboratories for application to inertial confinement fusion.[10] A 30-MV, 60-ns FWHM open circuit voltage pulse is used for the $\sin^2$ driver coupled to a 4.4-ohm generator impedance and a 140-nH inductor. A load impedance of 10 ohms is used for all cases. Three cases are shown, one without the switch, one with a switch at 25 cm cathode radius, and one with a switch at 15 cm. Both switch cases use a 15 cm/μsec switch plasma with C^{2+} densities of 2.6(12) and 4.4(12)cm^{-3} respectively such that both switches will open at the same current level. The switch lengths were both 20 cm.

One important aspect of this switch application is the relaxation of the vacuum interface voltage insulation requirements. One of the difficulties in designing high voltage pulse power generators is the limit of ~ 100 kV/cm electric field stess on a vacuum interface. Under ordinary circumstances the insulator must be able to withstand nearly the full diode voltage. With an inductive store/vacuum opening switch system the insulator must withstand only the voltage which charges the inductor through the closed switch. The insulator can be allowed to flash over as the switch opens thereby trapping the energy in the vacuum insulator close to the load. This effect is illustrated in Fig. 6a where the voltage on the generator side of the inductor, V_I, are shown for cases without the switch and with the switch at a 25 cm cathode radius. Without the switch the peak insulator voltage is 21.5 MV; with the switch the highest voltage is only 15.4 MV. The 6-MV change makes a significant difference in the design of the insulator.

Figures 6b, 6c, and 6d illustrate the waveshapes expected for this high voltage system with the switch. The solid lines in all three

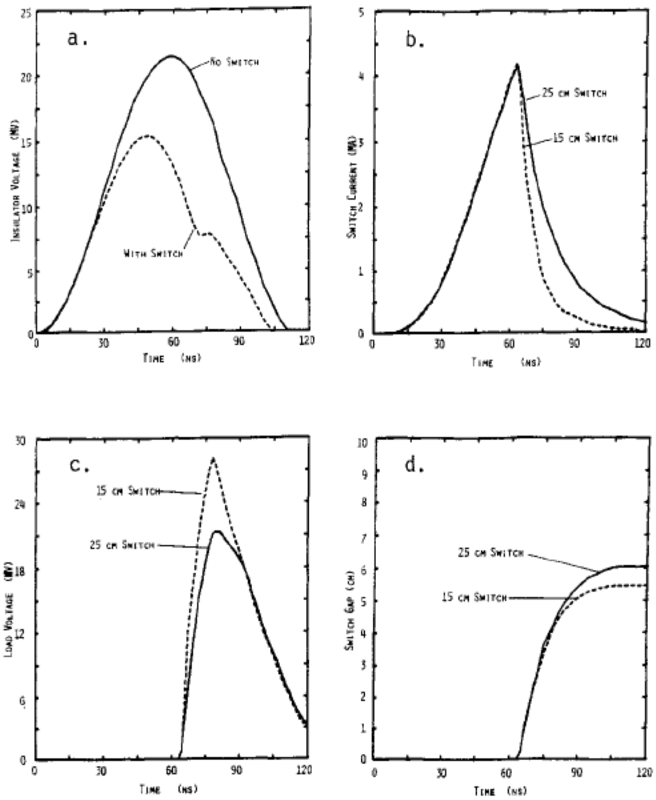

Fig. 6. Insulator voltage (a) with and without the switch, and switch current (b), load voltages (c), and switch gaps (d) for 25 and 15 cm radii switch systems.

figures show the switch current, load voltage and switch gap for the switch located at 25 cm radius. The switch current peaks at just over 4 MA at 60 ns into the generator pulse. The switch takes ~10 ns to open and delivers nearly half of the stored current to the 10-ohm load. The peak load voltage is 21 MV for this case. The switch gap at peak voltage is nearly 4.5 cm. Even with this large switch gap there is significant current (~1.5 MA). still going through the switch at peak voltage. This means that the switch has not fully opened. The 15-cm cathode radius case shows a considerable improvement over the 25-cm case. The switch current is identical until the switch opens, then it opens much quicker. The peak load current increases to 2.8 MA and the voltage jumps to 28 MV. The full 4 MA is not switched because the total current resistively decays during the opening time. The switch gap at peak voltage (t = 72 ns) has not changed much from the 25-cm case but the magnetic field in the switch region has increased significantly due to the smaller cathode radius. The increased magnetic field allows the higher voltage electrons to be better insulated from the plasma and the switch opens to higher impedances. This illustrates how the geometry of the switch can affect the switch operation. A more complete analysis of the scaling of PEOS operation to PBFA II has been presented elsewhere.[15,16]

Conclusions:

This paper has attemped to present some examples of the operation of the Plasma Erosion Opening Switch, illustrate the use of the switch model which has been developed, and to demonstrate the application of this model to scaling the switch to new regimes. It is clear from these examples that the PEOS offers a valuable tool to improve and extend the operation of existing pulse power devices.

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